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Assessment of the possibility of implementing small retention reservoirs in terms of the need to increase water resources

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Abstract: Currently, due to reduced water resources, there is a need to build reservoirs in Poland. Reservoirs perform important economic, natural and recreational functions in the environment, improve water balance and contribute to flood protection. In the construction of reservoirs, it is necessary to consider not only hydrological issues related to water quantity, but also its quality, silting, and many other factors. Therefore, the physiographic, hydrological, hydrochemical, and hydrogeological conditions of the projected reservoirs have to be taken into account to limit the potential negative effects of decisions to build them.

In order to assess the suitability of eight projected small water retention reservoirs (to increase water resources in the Barycz River catchment in Lower Silesia and Greater Poland provinces, this article takes into account hydrological indicators (efficiency of the reservoir, operation time, dependence on the intensity of silting, and flood hazard indicator), water quality (phosphorus load and nitrogen load), hydrogeological conditions (type of geological substratum for the reservoir basin and filtration losses), and safety of the reservoir dam.

To develop a theoretical model describing the regularities between the indicators, multivariate statistical techniques were used, including the Principal Component Analysis (PCA) and the Factor Analysis (FA). In order to assess the reservoirs, a synthetic indicator was developed to compare the reservoirs with each other in relation to the conditions. The Cluster Analysis (CA) was used for typological classification of homogeneous locations of projected small retention reservoirs.

Own research procedure for identification of the most advantageous water reservoirs, with the use of multivariate statistical techniques, may be used as a tool supporting decision making in other facilities intended for implementation in provincial projects of small retention.

Introduction

Currently, water management in river catchments is becoming increasingly important. The importance of water for humans and the natural environment is stressed in many political, social and economic debates. This is primarily due to the difficulties in providing good and clean water to all users which exist now or are likely to occur in the future. These difficulties result from limited resources and unfavorable changes in the structure of water balance (Kundzewicz et al. 2005; MGMiŻŚ, 2019b; Mioduszewski 2014) due to climate change and the resulting threats being one of the greatest challenges of today (Degórski 2018; Gruss & Wiatkowski 2018; Kubicz et al. 2021; Melo et al. 2016; O'Keeffe et al. 2019; Paruch et al. 2015; Tokarczyk & Szalińska 2018). Water reservoirs are built to counteract droughts and floods (Bus & Mosiej 2018; FitzHugh et al. 2010; Kałuża et al. 2017; Kowalewski 2008; Mioduszewski 2014; Wu et al. 2018). In recent years (from 2000 to 2019), small water reservoirs in Poland have been implemented under the Provincial Programs of Small Retention put into force by the provincial assemblies (DZMiUW, 2006; WZMiUW, 2015) and Wojewódzkie Zarządy Melioracji i Urządzeń Wodnych [Provincial Water Management Boards] (as of 1 January 2018, Państwowe Gospodarstwo Wodne Wody Polskie [State Water Farm Polish Waters]) (*Assumptions*, 2019). In view of the limited opportunities regarding the construction of large retention reservoirs in the upper and central Odra River basin due to the location and costs, the construction of small reservoirs seems justified (Wiatkowski 2010).

Small water reservoirs fulfil economic, agricultural, energy, natural, and recreational functions, and improve water balance. They provide important ecosystem-based services for aquatic and water-related organisms (Baumgartner et al. 2019; Cymes & Glińska-Lewczuk 2016; Gaupp et al. 2015; Markowska et al. 2019; Ignatius & Rasmussen 2016; Mioduszewski 2014; Wiatkowski et al. 2013). Water reservoirs are also used for tourism purposes (fishing, water sports, swimming) and increase the aesthetic value of the areas in which they are built (Mosisch & Arthington 2006; Tallar & Suen 2017; Wiatkowski et al. 2015). For the construction of water reservoirs, it is necessary to consider not only the quantity, but also the quality of water intended for retention. The existence and use of the reservoir may often be threatened by the pollutants which flow into it, contained mainly in water and river load [Bogdał et al. 2015; Czamara, et al. 2008; Junakova & Junak 2017; Miąsik et al. 2014; Mioduszewski 2014; Pütz & Benndorf, 1998; Szoszkiewicz et al. 2016; Tomczyk et al. 2020; Waligórski et al. 2018; Wiatkowski & Paul 2009; Wiatkowski & Rosik-Dulewska 2015] or resulting from its silting (Kasperek et al. 2013; Sojka et al. 2019). Therefore, it is necessary to properly determine the conditions for reservoirs and take them into account at the planning stage (Wiatkowski et al. 2018).

From the practical point of view, the important and difficult challenge of hydraulic engineering is to assess the suitability of small retention reservoirs, taking into account the conditions resulting from the specific location defined in the project. For this purpose, various techniques of exploratory data analysis can be used to group objects with similar characteristics and detect similarities (Wiatkowski & Wiatkowska 2019).

At the planning stage, for the implementation of small retention reservoirs, many local physiographic, hydrological, hydrochemical, and hydrogeological conditions have to be taken into account and multivariate analyses need to be carried out, e.g. with the use of multivariate statistical techniques, to limit potential negative effects of decisions to build such facilities. The aim is to enable the selection of the most advantageous facility out of all the projected ones. Thus, in terms of the need to increase water resources, it is necessary to assess the suitability of water reservoirs. This is in line with the standards specified by the EU and national acts (*Water Framework Directive 2000/60/EC of the European Parliament and of the Council*; *Water Law 2017*; *National Water Policy Project 2011*).

In the field of monitoring and evaluation of the improvement of water quality and water quantity in water reservoirs, multivariate comparative analysis methods are increasingly used, including Principal Component Analysis (PCA), Factor Analysis (FA), and Cluster Analysis (CA) (Boyacioglu & Boyacioglu 2008; Boyacioglu 2006, 2014; Voza et al. 2015; Karimian et al. 2018; Przybyła et al. 2015; Wiatkowski & Wiatkowska 2019; Sojka et al. 2019; Myronidis & Ivanova 2020). Object grouping methods are also used to separate homogeneous catchments and determine how similar they are in terms of conditions (Laacha & Blöschl 2006; Cupak et al. 2017). This paper proposes the use of multivariate statistical techniques to assess the suitability of small retention reservoirs and select the most advantageous ones.

The aim of the study was to assess the suitability of eight small water reservoirs located in the Barycz River catchment in the Lower Silesia and Greater Poland Provinces, in south-western Poland, in terms of the need to increase water resources.

For this purpose, multivariate methods of statistical data analysis were applied. Based on the procedures under the hierarchical taxonomic methods, the planned reservoirs were classified in terms of their suitability. The Principal Component Analysis (PCA) and the Factor Analysis (FA) were used to develop a theoretical model describing the regularities between the indicators determining the possibilities of implementing projected reservoirs in the Barycz River catchment. The Cluster Analysis (CA) was used for typological separation (agglomeration) of homogeneous locations of projected small retention reservoirs. The analyses were performed based on hydrological conditions (efficiency of the reservoir, operation time depending on the intensity of silting, flood hazard indicator), water quality (phosphorus load and nitrogen load), hydrogeological conditions (type of geological substratum for the reservoir basin and filtration losses) and safety of the reservoir dam.

Description of the research area

The Barycz River is 136,17 km long. It is a lowland river which flows into the Odra River at 378,2 km. Its catchment area is 5543,36 km^2. The catchment is asymmetric. Its right bank has more tributaries. Along the entire route of the river, there are a number of weirs, altering the flow of water, mainly for ponds and meadow irrigation. The watercourses which flow into it are similar. The Barycz River stands out with a dense and complex drainage system, intensive water management and a number of hydrotechnical facilities. As a result, it is extremely difficult to determine water resources in the entire catchment area (Marcinkowski et al. 2017; Tokarczyk-Dorociak & Gębarowski 2011). The key left-hand tributaries include the Polska Woda (53,98 km), the Sąsiecznica (43,70 km), the Złotnica (37,24 km), and the Malinowa Woda (36,78 km). The key right-hand tributaries include the Orla (95,11 km), the Rów Polski (63,53 km), the Dąbroczna (41,55 km), and the Kuroch (32,38 km).

The Barycz River catchment has eight gauging stations; some of them are located on the Barycz River (Łąki, Odolanów, Osetno), while the others on its tributaries, i.e. the Kuroch (Odolanów), the Orla (Korzeńsko), the Polska Woda (Bogdaj), the Polski Rów (Rydzyna), and the Sąsiecznica (Kanclerzowice) (Chłopek 2018). Table 1 presents hydrological data for selected water gauge cross-sections in the Barycz River catchment.

The Barycz River catchment is mostly covered by arable land accounting for 50.86% of the catchment area. Forests cover 29.69% of the area (coniferous forests predominate). Urban areas represent a small percentage of the area. The low-density development prevails (Fig. 1).

Anthropogenic areas cover a total of 5.12% of the catchment area. Water reservoirs are located mainly in the central and eastern part of the catchment and constitute 4.17% of the total area (GIOS, 2018).

Based on the analysis of the needs for water collection in the Barycz River catchment, the locations for eight water reservoirs were selected under the Regional Small Retention Programs for the Lower Silesia and Greater Poland provinces (*Programme 2006*, *Programme 2015*), (Fig. 2) (Chłopek 2018).

Methodology

Hydrology

The amount of water that can be stored in the reservoir depends primarily on the amount of water flowing from the catchment to the reservoir, the catchment area, and the available space to create the reservoir resulting directly from its capacity. The operation of water reservoirs is described with the use of the following indicators, defined by Dziewoński (1973), Ciepielowski (1999), and Michalec et al. (2016); i.e. reservoir compensation indicator, meaning water outflow in relation to the average annual outflow, reservoir annual volume, meaning reservoir capacity in relation to the average annual outflow, and the reservoir efficiency.

Due to the lack of information on precise plans regarding the use of the reservoirs, it was assumed that the entire available capacity of the water storage facility would be used and that potential water recipients would use the entire annual outflow, keeping the minimum acceptable flow in the watercourse, including the current needs occurring below the analyzed cross-section.

Since the water gauge cross-sections (Table 1) do not coincide with the calculated sections for eight projected reservoirs, the paper uses the extrapolation to transfer hydrological information (Mansanarez, et al. 2019), from the period between 1981 and 2010. The data have been obtained from the Institute of Meteorology and Water Management – National Research Institute and then processed.The minimum acceptable flow in the analyzed cross-sections was determined on the basis of the Kostrzewa method (1977 in: Wilk & Grabarczyk 2018). All formulas necessary for hydrological calculations are presented in Table 2 (Dziewoński, 1973; Kostrzewa, 1977 in: Wilk & Grabarczyk 2018; Mansanarez et al. 2019; Michalec et al. 2016).

Table 1. Characteristic flows in the Barycz River catchment, 1981–2010 (*Conditions*, 2012)

Watercourse (Gauging station)	Catchment [km^2]	Q_m [m$^3 \cdot$s^{-1}]	SNQ [m$^3 \cdot$s^{-1}]	NNQ [m$^3 \cdot$s^{-1}]
Barycz (Łąki)	1752.11	5.945	0.915	0.200
Barycz (Odolanów)	162.58	0.855	0.146	0.020
Barycz (Osetno)	4579.55	14.544	1.619	0.260
Kuroch (Odolanów)	168.90	0.484	0.035	0.005
Orla (Korzeńsko)	1224.77	4.457	0.315	0.060
Polska Woda (Bogdaj)	126.90	0.550	0.067	0.098
Polski Rów (Rydzyna)	334.10	1.058	0.106	0.019
Sąsiecznica (Kanclerzowice)	389.60	1.376	0.142*	0.000

* 1991–2001

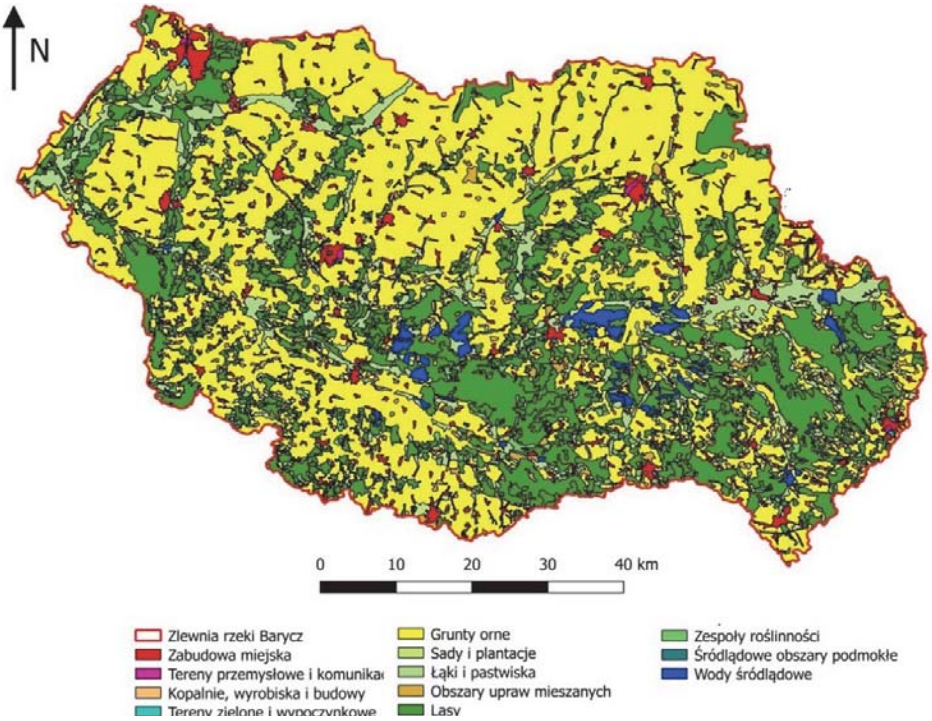


Fig. 1. Forms of land use in the Barycz River catchment (GIOŚ, 2018)

Water quality

Water quality was assessed on the basis of own research carried out for the cross-sections of projected reservoirs and the research results obtained from the Provincial Environmental Protection Inspectorate (WIOŚ) in Wrocław and Poznań (WIOŚ, 2011, 2013, 2015, 2016). Own research was conducted four times in the period between April 2017 and May 2018 in four locations (Baby, Sulmierzyce, Szklarka Myślniewska, and Zawidze). The WIOŚ research was conducted in different years under the 2018 surface water monitoring and covered surface water bodies (SWBs). Seven SWBs were selected, closest to the projected locations, i.e. the Kuroch, the Złotnica, the Czarna Woda, the Orla – from the spring to the Rdęca, the Śląski Rów, the Łacha, and the Sąsiecznica.

In the field research, samples were taken with the use of water buckets and transferred to 1.5 liter bottles properly protected from the sun and high temperatures. Next, laboratory tests were performed in the Faculty of Environment Research Laboratory at the Wrocław University of Environmental and Life Sciences. The tests were carried out with the use of standard reference methods described in the standards for the following physicochemical parameters: pH, electrolytic conductivity (EC), dissolved oxygen (DO), five-day biochemical oxygen demand (BOD_5), total suspension (SUSP), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N), total Kjehdahl nitrogen (TKN), total nitrogen (TN), phosphate phosphorus (PO_4-P), and total phosphorus (P).

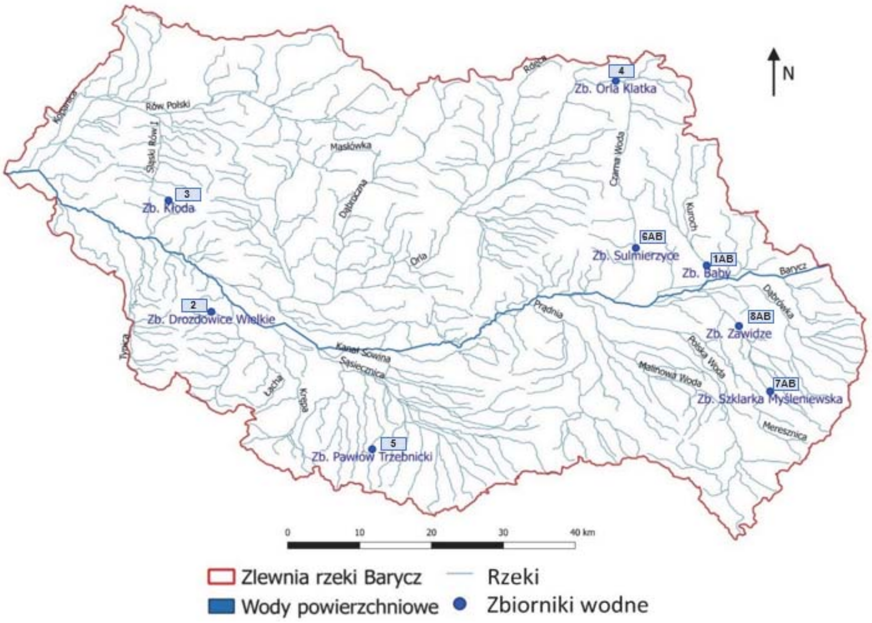


Fig. 2. Locations of the water reservoirs (KZGW, 2017)

Table 2. Formulas for hydrological parameters

Determined parameter	Formula	Notes
Reservoir compensation indicator α	$\alpha = \frac{V_w}{V_o}$	– V_w – available outflow from the reservoir [thousand m^3 per year] – V_o – the mean annual outflow from multiperiod [thousand m^3 per year]
Indicator of the reservoir capacity to the mean annual outflow B	$B = \frac{V_z}{V_o}$	– V_z – completely reservoir capacity [thousand m^3 per year]
Reservoir efficiency indicator E	$E = \frac{\alpha}{\beta} = \frac{V_w}{V_z}$	– α – reservoir compensation indicator – β – reservoir annual volume
Minimum acceptable flow Q_i	$Q_i = k \cdot SNQ$	– SNQ – mean-low flow in the cross-section [$m^3 \cdot s^{-1}$] – k – parameter which depends on type of the river and size of the catchment [–]
Available flow Q_{av}	$Q_{av} = Q_{au} - Q_i$	– Q_{au} – natural design flow [$m^3 \cdot s^{-1}$]
Transfer of hydrological information (by extrapolation)	$Q = Q_0 \left(\frac{F}{F_0}\right)^n$	– Q – flow in the water gauge profile (WWQ) [$m^3 \cdot s^{-1}$] – Q_0 – flow in the reference profile [$m^3 \cdot s^{-1}$] – F_0 – catchment area in the reference profile [km^2] – F – catchment area in the tested profile [km^2] – n – exponent which depends on the flow characteristics [–]

The results of physicochemical studies were analyzed on the basis of the applicable Regulation of the Minister of Marine Economy and Inland Navigation of 11 October 2019 (Dz.U. [Journal of Law] of 2019, item 2149) for type 17 natural watercourses (lowland, sandy stream) (MGMiŻŚ, 2019a). The ecological potential of SWB was assessed on the basis of the results of biological, hydromorphological, and physicochemical tests performed by WIOŚ.

The analysis of physicochemical parameters was complemented by the assessment of the degree of eutrophication risk in water reservoirs, using the Vollenweider model (1992), the Kajak method (2001), and the assessment of the trophic status based on the Carlson's index (1976). In the case of the former, the following results were used: the average annual results for mean annual flow (Q_m) obtained from the water gauge cross-sections located in the Barycz River catchment for the period between 1981 and 2010 (Odolanów, Łąki, Osetno, Bodgaj, Kanclerzowice, Korzeńsko, and Rydzyna), mean total phosphorus concentration C_P, for own points and the ones obtained from WIOŚ research, the mean depth of each of the projected water reservoirs (D_R), and the mean water retention time in the water reservoir (RT_R). The formulas which were used in this method are presented in Table 3. They relate to various parameters necessary to determine the trophic status. The obtained result refers to the dangerous phosphorus load (DL_P) and the permissible phosphorus load (PL_P). The values below PL_P are typical of oligotrophic waters (with no risk of eutrophication, the lowest productivity, low phosphorus load, and high dissolved oxygen content). The values between DL_P and PL_P refer to mesotrophic waters (with a medium risk of eutrophication). The values above PL_P relate to eutrophic waters (with a high risk of eutrophication and characteristics opposite to oligotrophic waters). Permissible and dangerous load of phosphorus and nitrogen were determined on the basis of research by Vollenweider (1992). In this case, the relationship between DR_T (average depth of reservoir/water retention time in reservoir; m/year) and AL_P (phosphorus reservoir loading; g m^{-2} year^{-1}) is used. These values are plotted on a graph which plots the obtained DR_T (X axis) and AL_P (Y axis) values for each of the objects. In the last step, the risk of reservoir eutrophication TE_P depending on the phosphorus load was determined based on previously calculated values for the dangerous level.

In the Kajak method (2001), the mean annual flow (Q_m) and the average annual concentration of total nitrogen (C_N) in the tested points were also used for calculations. The calculated values of the actual nitrogen load were checked against the dangerous nitrogen load (DL_N), with respect to the trophic status, determined at 2 g · m^{-2} · a^{-1} N of nitrogen per year per 1 m^2 of the reservoir. The formulas necessary for the calculations are shown below in Table 3.

In order to compare the obtained results, the trophic state index (Carlson's index) depending on the phosphorus load was determined for water reservoirs (Table 4). On the basis of the index, the trophic status for the corresponding waters was determined for each measuring point (Table 4) (Vollenweider, 1965; Sakamoto, 1966; EPA Survey, 1974; Carlson & Simspon, 1996; Maloney 1979].

Table 3. Formulas for determining the risk of reservoir eutrophication – Vollenweider method (phosphorus, 1992), Kajak method (nitrogen, 2002), and Carlson index (trophic state index, 1976)

Determined parameter	Formula	Notes
Ratio DR_T of mean depth of the reservoir to mean retention time in the reservoir	$DR_T = D_R/RT_R$	– D_R – mean depth of the reservoir [m] – RT_R – mean retention time in the reservoir [year]
Actual phosphorus load AL_P	$AL_P = C_P \cdot Q_m$	– C_P – average annual concentration of phosphorus [g/l] – Q_m – mean annual flow [l/year]
Risk of reservoir eutrophication TE_P depending on the phosphorus load	$TE_P = AL_P/D_{LP}$	– DL_P – dangerous phosphorus load [g/m^2 · year]
Actual nitrogen load AL_N	$AL_N = C_N \cdot Q_m$	– C_N – average annual nitrogen concentration [g/l]
Risk of reservoir eutrophication TE_N depending on the nitrogen load	$TE_N = AL_N/D_{LN}$	– DL_N – dangerous nitrogen load [g/year]
Trophic state index (Carlson)	$TSI_P = 14.42 \ln C_P + 4.15$	–

Table 4. Trophic status of reservoirs based on the Carlson's index, depending on the phosphorus load (TSI_P) (Carlson, 1976)

Reference / Trophic status	Vollenweider (1965)	Sakamoto (1966)	EPA Survey (1974)	Carlson & Simpson (1996)
Oligotrophy	< 10	< 20	< 10	< 6
Oligo-mesotrophy	10–20	–	–	6–12
Mesotrophy	20–50	20–50	10–20	12–24
Mesoeutrophy	50–100	–	–	24–48
Eutrophy	> 100	> 50	> 20	48–96
Hypereutrophy	–	–	–	> 96

Statistical significance of the differences between mean concentrations of physicochemical parameters in measuring profiles of individual reservoirs was performed based on the analysis of variance using the ANOVA test, at the significance level $\alpha = 0.05$. The analyses were performed with the use of the R statistical analysis software.\

To analyze the relationships between physicochemical parameters for the analyzed reservoirs, the Principal Component Analysis (PCA) was used. For calculations, the ‘prcomp’ package was used.

Intensity of silting

The intensity of silting of the projected reservoirs was determined by calculating the parameters which indicate the capacity to permanently retain the river load (accumulation capacity) and by determining the parameters which indicate the amount of river load deposited in the reservoir, both in quantitative terms and over time (volume deposited after the operation time and mean annual mass of sediments). In the final step, the time of use of each of the reservoirs depending on the reduction of their volume as a result of river load accumulation is determined. This is done on the basis of nomograms (the Churchill method). It is assumed that the limit of the decrease in the reservoir’s volume is 80% beyond which its further operation is impossible. All formulas necessary to calculate the intensity of silting are presented in Table 5 (Madeyski, et. al 2008; Lewis et al. 2013).

Criteria for the suitability of the projected small retention reservoirs

Multivariate techniques of exploratory data analysis were used to analyze and evaluate the suitability of eight small retention reservoirs in terms of their locations in the Barycz River catchment. The aim was to recognize the variability and structure of indicators which determine the suitability of the projected reservoirs, taking into account hydrological criterion, water quality, intensity of silting, geological substratum, and safety.

The hydrological criterion includes the reservoir efficiency indicator (E) for multicriteria comparative analysis of the reservoirs (Table 2). The indicator is a measure of the potential of supply and water retention of the reservoir, which depends not only on the physiographic conditions of the catchment, but also on the available space to create the reservoir basin. The hydrological criterion also includes the operation time (t) which describes the silting process intensity in individual reservoirs (Table 2). Small retention dammed reservoirs not only provide water retention, but also prevent flood and reduce short-term high water levels occurring in small catchment areas. Therefore, this factor was also included in the analysis. The flood index (K) was proposed to be able to compare water level peaks in the catchments which vary in size. The index is based on the flow rate and the area of catchment (Bartnik & Jokiel 2007) (Table 6). The higher the value of K, the more the catchment area of the river is susceptible to the occurrence of flood. According to Byczkowski (1996), in small catchments below 100 km^2, K does not exceed 4.5.

Table 5. Formulas necessary to determine the intensity of silting (Madeyski et al., 2008; Lewis et al., 2013)

Determined parameter	Formula	Notes
Sedimentation indicator SI	$SI = RT_R/V_R$	– RT_R – mean retention time in the reservoir [s] – V_R – mean water velocity in the reservoir [m/s]
Accumulation capacity β for the river load	$\beta = [100 - (800 \cdot SI^{-0,2} - 12)] \cdot 100\%$	–
Turbidity Δ	$\Delta = J \cdot a \cdot b \cdot c \cdot 10^5$	– J – mean local watercourse drop [–] – a – coefficient of surface erosion depending on the ground slope and the type of land [–] – b – coefficient of deep-seated erosion depending mainly on the type of land [–] – c – compensation factor depending on the catchment annual volume [–]
Mean annual mass D_u of the river load flowing into the reservoir	$D_u = V_o \cdot \Delta \cdot 10^{-6}$	– V_o – sum of the annual average multiannual outflow [m^3]
Volume D_1 of the river load deposits after the first year of operation	$D_1 = \dfrac{\beta \cdot D_u}{\rho_b}$	– ρ_b – sediment volume density [t · m^3]
Deposit volume Z_t after the operation time t	$Z_t = V_i \cdot \left[1 - \left(1 - \dfrac{D_1}{V_i}\right)^t\right]$	– V_i – initial capacity of the reservoir [m^3] – t – operation time [year]

Table 6. Formula determining the flood index (Bartnik & Jokiel, 2007)

Determined parameter	Formula	Notes
Flood index K [–]	$K = 10 \cdot \left[1 - \left(\dfrac{Log Q_{max} - 6}{Log F - 8}\right)\right]$	– Q_{max} – maximum flow [m$^3 \cdot$s^{-1}] – F – catchment area [km^2]

In view of the fast-progressing processes of eutrophication in small retention reservoirs, which is mainly due to their low depth in relation to the surface and to the fact that the catchment areas they are located in are used mainly for agricultural purposes, the degree of risk of eutrophication is also included in the analysis. For the assessment of the suitability of the projected reservoirs, the water quality criterion includes the load of individual reservoirs with biogenic substances. This includes the risk of reservoir eutrophication depending on the phosphorus load (TE_P) and the nitrogen load (TE_N) (Table 3).

Owing to the fact that the construction of small water reservoirs on a substrate with a high water permeability coefficient generates additional costs connected with the execution of the basin seals, the effectiveness of which cannot be taken for granted (Adamski et al., 1986), the assessment of the suitability of the projected reservoirs in the Barycz River catchment also includes their geological substratum. Soil conditions for the locations were assessed based on the permeability of surface formations, determined on the basis of the Detailed Geological Map of Poland on a scale of 1:50000 made available by the Polish Geological Institute (PIB), and classification of soil formations on the basis of their filtration properties specified by Pazdro & Kozerski (1990). The approximate amount of water permeating through the reservoir basin was determined on the basis of filtration loss coefficient (Dziewoński, 1973). In order to compare the locations, unit filtration losses q_p per 1 ha ($m^3 \cdot d^{-1} \cdot ha^{-1}$) were calculated (Table 7).

In the last criterion included in the analysis, the safety of water reservoirs and potential risk for each reservoir were determined. The implementation of the low-efficiency and high-risk investment in the field of small retention reservoirs is undesirable. To identify the risk, a safety hazard indicator was used. The indicator describes the damming height and the volume of the reservoir (Table 8) and is commonly used in analyses, e.g. by the French Committee on Large Dams (Degoutte 2002).

In order to assess the suitability of the projected reservoirs, the taxonomic method for linear arrangement of multi-feature objects was used. The method is commonly used in a variety of areas in regional, natural, agricultural, and economic research (Wiatkowska & Słodczyk 2018). The method was applied to classify the reservoirs in terms of linear hierarchy according to their suitability. The linear arrangement of multivariate objects is based on the order binary relation. Based on its axioms, it is possible, for example, to determine which of the two objects is better (the first one) and which one is worse (the second one), and to specify whether they are identical. In the first stage of this analysis, partial indicators were verified in terms of their statistical variability, and descriptive statistics with measures of distribution were calculated (Myronidis et al. 2018). Multivariate methods assume the elimination of those variables which do not objectively describe the research area (objects) or are in high correlation with other variables and do not significantly affect the result of comparison. As the criterion for the selection of final indicators, the following was assumed: the threshold level of coefficient of variation $V > 10\%$ and Pearson and Spearman correlation coefficient $r < 0.7$.

In order to make the indicators comparable to each other in terms of a number of criteria, standardize the units of measurement and orders of magnitude of the indicators, and determine a synthetic indicator of the potential for reservoir location, the indicators were properly described in the next step. Stimulants were assumed for those indicators whose high values are desirable for the implementation of small reservoirs while destimulants were assumed for those indicators whose high values indicate unfavorable conditions and some obstacles to the implementation of small retention facilities. Partial indicators were normalized by means of the zero unitarization method (Lindsey et al. 2018; Wiatkowska & Słodczyk 2018) (Table 9). The values of all indicators were transformed into the range [0–1]. "1" was assigned to the reservoir with the highest value of a given partial indicator, and "0" was assigned to the reservoir with the lowest value, out of all the reservoirs (Table 9).

Synthetic location indicator S_l for each projected investment (in the form of a latent variable) was constructed by the summation of standardized values of partial indicators describing the reservoirs (Table 9) (Panek & Zwierzchowski 2013). This method was selected because it can be used even if maximum values for stimulants are not optimal – based on the statistical criterion with the arithmetic mean ($\bar{S}_l$) and standard deviation (S_{S_l}) from the synthetic location indicator S_l, of the projected reservoir locations (Table 9).

A theoretical model was also developed to describe the relationships and the influence of particular partial indicators on the location potential of the projected reservoirs in the Barycz

Table 7. Formula determining unit filtration losses (Dziewoński, 1973)

Determined parameter	Formula	Notes
Unit filtration loss coefficient q_p per 1 ha [$m^3 d^{-1} ha^{-1}$]	$q_p = k \cdot A \cdot \frac{H}{L} \cdot 86400$	– k – substrate filtration coefficient [$m \cdot s^{-1}$] – A – lagoon area [m^2] – H – water depth at the damming structure[m] – L – distance from the centre of gravity of the lagoon to the damming structure [m]

Table 8. Formula determining the safety hazard indicator (Degoutte, 2002)

Determined parameter	Formula	Notes
Safety hazard indicator	$b = H^2 \sqrt{V}$	– H – damming height [m] (water depth at the damming structure [m]) – V – reservoir volume [hm^3]

River catchment. For this purpose, the Principal Component Analysis (PCA) was applied. The method reduces the number of variables by transforming the initial variables into a set of new, independent and mutually orthogonal variables forming a theoretical model which describes the relationships between the attributes (Shrestha & Kazama 2007; Stathis & Myronidis 2009).

The number of principal components was identified on the basis of the Kaiser criterion. Based on this criterion, the components that correspond to eigenvalues higher than one were accepted for further analyses (Singh et al. 2005). The components were interpreted on the basis of the Factor Analysis (FA), describing the contribution of a given partial indicator to the individual principal components.

The analysis of the similarity of the projected reservoirs depending on the synthetic location indicator for the projected investment S_l was also performed. For this purpose, the cluster analysis (CA) was applied. This is an unsupervised pattern recognition technique used to classify objects into possibly homogeneous internal clusters based on their similarity (Voza et al. 2015; Sojka et al. 2019). Hierarchical clustering was performed using the Ward's method which is often used in hydrology and climatology studies. It differs from other clustering methods in that that the distance between clusters is estimated on the basis of the analysis of variance and, at each stage, out of all possible cluster pairs, only the one which leads to a minimum cluster variance after merging is selected (Rao & Srinivas 2008; StatSoft, 2011). The square of the Euclidean distance was used to describe the distance between clusters (Singh et al. 2005; Pejman et al. 2009; Varol et al. 2012). All calculations were performed in Statistica 13.1.

Research results and discussion

Hydrology

The hydrological information obtained from the water gauge cross-sections was transferred to the sections of the proposed reservoir locations. The characteristic flows obtained in this way are presented in Table 10. Due to the lowland type of watercourses and small area of the catchment, the minimum acceptable flow, for most watercourses, was calculated for k = 1. Only for two watercourses (Szklarska Myślniewska and Pawłów Trzebnicki), the minimum acceptable flow was calculated for k = 1.27, due to the sub-mountain character of this watercourses. The highest value of Q_{au} was obtained for the Kuroch River in the Baby profile ($Q_{au} = 0.452$ m^3·s^{-1}) and the lowest value for the Kłoda profile on the Polski Rów River ($Q_m = 0.023$ m^3·s^{-1}). Similarly, the highest value of available flow was obtained for the Baby reservoir ($Q_{av} = 0.033$ m^3·s^{-1}) and the lowest value for the Kłoda reservoir ($Q_d = 0.002$ m^3·s^{-1}) (Table 6). In terms of maximum flows in the profiles of the projected reservoirs (Table 6), the highest value was determined for the Zawidze profile ($Q_{max} = 72.4$ m^3·s^{-1}) and the lowest value for the Kłoda profile ($Q_{max} = 0.3$ m^3·s^{-1}).

Table 9. Formula determining the synthetic location potential indicator

Determined parameter	Formula	Notes
Normalised value of the stimulant indicator Z^S_j	$Z_j^S = \frac{x_j - min\ x_j}{max\ x_j - min x_j}$	– min x_{ij} – minimum value of the j-th indicator [–] – max x_{ij} – maximum value of the j-th indicator [–]
Normalised value of the destimulant indicator Z^D_j	$Z_j^D = \frac{max\ x_j - x_j}{max\ x_j - min x_j}$	– min x_{ij} – minimum value of the j-th indicator [–] – max x_{ij} – maximum value of the j-th indicator [–]
Synthetic location indicator for the projected investment S_l	$S_l = \frac{1}{p}\sum_{j=1}^{n} Z_j$	– Z_j – normalised value of the stimulant Z^S_j and destimulant Z^D_j indicator in *i*-th water reservoir (*l* = 1, 2,…, m = 8) [–] – p – number of indicators
Class I Class II Class III Class IV	$(S_l \geq \bar{S}_l + S_{S_l})$ $(\bar{S}_l + S_{S_l} > S_l \geq \bar{S}_l)$ $\bar{S}_l > S_l \geq \bar{S}_l - S_{S_l}$ $(S_l < \bar{S}_l - S_{S_l})$	– S_l – synthetic location indicator for the projected investment – $\bar{S}_l$ – arithmetic mean of the synthetic location indicator S_l [–] – S_{S_l} – standard deviation from the synthetic location indicator S_l [–]

Table 10. Characteristic flows in the cross-sections of reservoir locations

Reservoir	F [km^2]	SNQ [m^3·s^{-1}]	Q_m [m^3·s^{-1}]	Q_n [m^3·s^{-1}]	Q_d [m^3·s^{-1}]	Q_{max} [m^3·s^{-1}]
Baby	157.79	0.033	0.452	0.033	0.033	15.3
Drozdowice Wielkie	18.39	0.007	0.065	0.007	0.007	15.4
Kłoda	7.18	0.002	0.023	0.002	0.002	0.3
Orla Klatka	102.47	0.026	0.373	0.026	0.026	8.9
Pawłów Trzebnicki	11.16	0.004	0.035	0.005	0.005	0.9
Sulmierzyce	88.02	0.018	0.252	0.018	0.018	7.6
Szklarka Myślniewska	20.75	0.011	0.090	0.014	0.014	17.3
Zawidze	86.71	0.046	0.376	0.046	0.046	72.4

The efficiency indicators are presented in Table 11. All cross-sections have a very similar compensation indicator α = (0.84, 0.90). This results from the similarity of unit outflows (the reservoirs are located within a single catchment area, i.e. the Barycz River catchment). Thanks to the reservoir efficiency indicator (E), the reservoirs can be compared. The highest value of supply efficiency was achieved in Orla Klatka reservoir (78.8) and the lowest value in Pawłów Trzebnicki (10.4). The water retention capacity is more than twice as high as for other reservoirs. The lowest values of E were obtained for Pawłów Trzebnicki and the Kłoda for which the average annual available flows are only 0.030 $m^3 \cdot s^{-1}$ and 0.021 $m^3 \cdot s^{-1}$.

Water quality

The physicochemical parameters indicate strong contamination at the tested points (Table 12). Since physicochemical parameters covered by the regulation under which the assessment was made were repeatedly exceeded, it was assumed that the waters are below the ecological potential at each point. The lowest concentrations of parameters in total were recorded in Szklarka Myślniewska and Zawidze (points tested by WIOŚ) and the highest in Baby (WIOŚ) and Pawłów Trzebnicki (only one parameter normal: phosphate and pH respectively). Note that BOD_5 was not within the norm at each point. This may indicate an excess of organic compounds which may cause the development of unfavorable silting and eutrophication processes. These are the conditions under which the activity of microorganisms consuming oxygen for decomposition is very high. This is confirmed by the results of the total suspension as its limit values were also exceeded (about 20 mg/l while the norm is 11.8). In terms of biogenic substances, a very good or good potential for ammonium nitrogen was recorded for half of the points, which indicates low pollution from human activities. The area is poorly urbanized and the distance from human settlements is quite considerable. Arable land is the most common type of land use. As a result, various forms of nitrogen and phosphate phosphorus are frequently exceeded. This is probably due to fertilizers and crop protection products, herbicides, and pesticides flowing down from arable fields (Łabaz et al. 2014; Borek 2018). However, while there is a threat from phosphate phosphorus, there were many places in which total phosphorus was not exceeded. Nutrients significantly increase the productivity of water reservoirs, used by algae, and contribute to the development of eutrophication which affects not only the properties of water, but also the living conditions of organisms and usefulness of reservoirs, e.g. as a source of drinking water. The reservoirs most exposed to the development of eutrophication include Orla Klatka (the limit values for total nitrogen exceeded over 10 times) and Kłoda (the value of phosphate concentration 100 times higher than specified in the regulation). In these areas of waters, corrective measures must be applied (Moss 2007).

In order to assess whether corrective measures are needed in SWBs, the ecological potential is determined. The monitoring studies carried out by WIOŚ (Table 13) show that such corrective measures should be adopted in each of the measuring and control points of SWB because the ecological potential did not reach good potential (under the Water Framework Directive following international agreements, good ecological potential has to be achieved by 2020). In the analyzed points, the potential was poor (SWB Kuroch, Baby reservoir) or moderate (other points of SWB). The result was bad mainly because the limit values of physicochemical elements, especially biogenic substances, were exceeded (Table 13). The Sulmierzyce and Pawłów Trzebnicki reservoirs are likely to fit into the existing agricultural landscape. The potential of biological elements in these areas was good. In the case of the Baby reservoir, the investment should be approached very cautiously. Once the ecological balance is disturbed, it is much more difficult to ensure environmental compensation, i.e. restore the former natural value to the investment areas, or to initiate restoration, i.e. increase the environmental value of the area, e.g. by using grids that prevent fish from entering the hydroelectric power plants built prior to the water reservoirs or fish ladders that bypass hydrotechnical structures (Larinier 2008; Bănăduc et al. 2018).

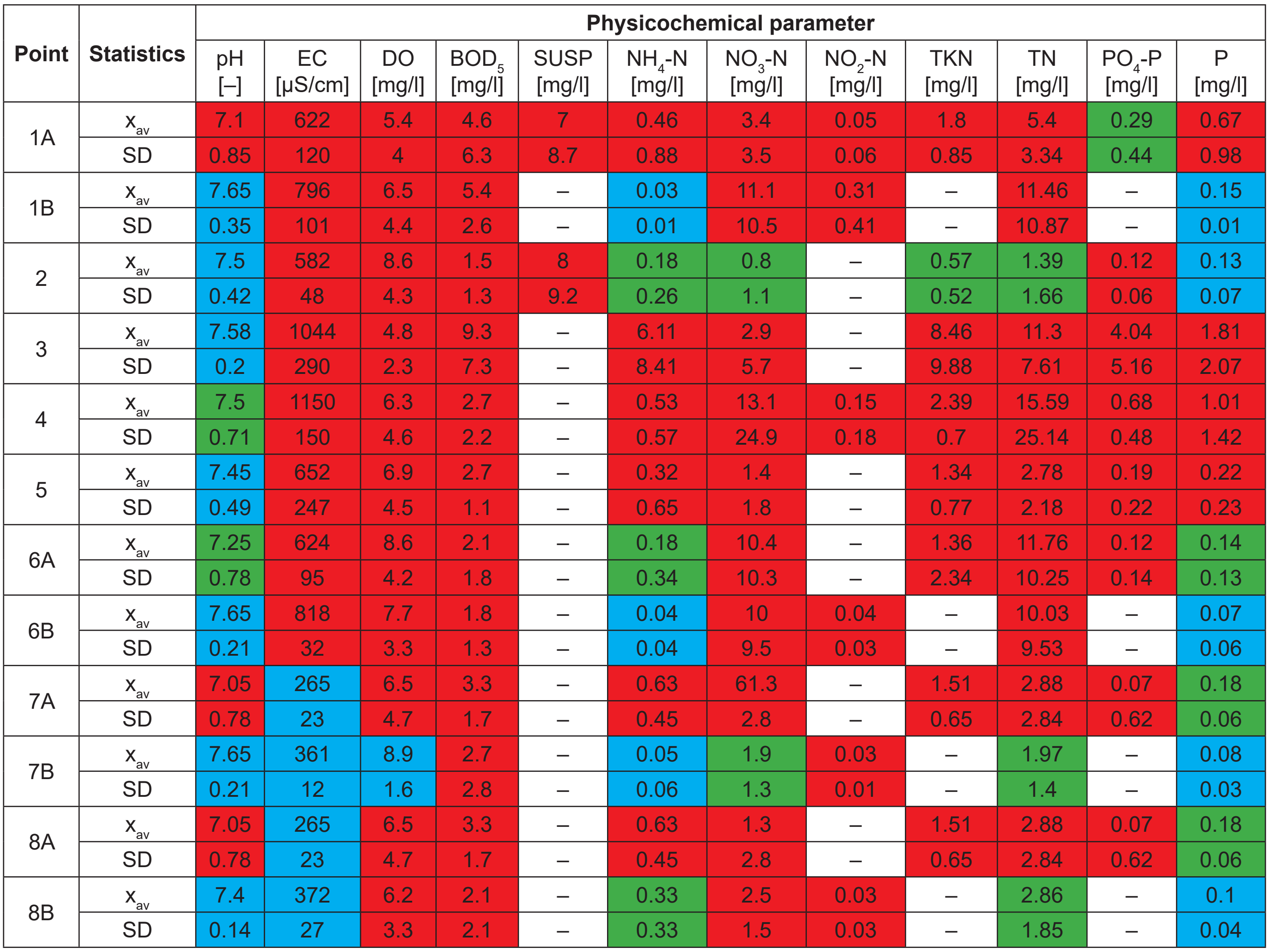
It is often the case that the water stored in the reservoir degrades and loses its usefulness, and blooms occur (Dodds et al. 2016; Miąsik et al. 2014; Wiatkowski & Czerniawska-Kusza 2009). The quality of water feeding the reservoir results mainly from the method of water and sewage management in the catchment. Phosphorus and nitrogen compounds are the factors which significantly affect the quality of water in the reservoir (Kostecki et al. 2017; Koszelnik 2014; Pütz & Benndorf, 1998; Wiatkowski & Paul 2009; Wiatkowski 2010). In order to examine a real risk of eutrophication in the reservoirs, the trophic status should be determined. Water reservoirs feature the natural succession resulting from the activity of aquatic organisms, the supply of organic substances and inorganic fertilizers (especially phosphorus and nitrogen compounds), and the origin of the reservoir, i.e. natural processes, e.g. glacier or river activity, or

Table 11. Efficiency indicators for the reservoirs (Chłopek, 2018)

Reservoir	V_z [1000 m^3 per year]	V_o [1000 m^3 per year]	V_w [1000 m^3 per year]	α	B	E
Baby	193	14259.42	12867.36	0.9	0.014	66.67
Drozdowice Wielkie	56	2048.27	1762.91	0.86	0.027	31.48
Kłoda	40	717.03	620.05	0.86	0.056	15.5
Orla Klatka	135	11759.57	10637.57	0.9	0.011	78.8
Pawłów Trzebnicki	90	1114.5	941.33	0.84	0.081	10.46
Sulmierzyce	282	7954.33	7177.8	0.9	0.035	25.45
Szklarka Myślniewska	110	2836.13	2369.71	0.84	0.039	21.54
Zawidze	405	11851.6	9902.55	0.84	0.034	24.45

artificial processes, e.g. building dams on rivers, creating water reservoirs, digging up reservoirs for breeding purposes, etc. (Grimard & Jones 2011). There are various reservoirs depending on their trophic level (productivity and enrichment with organic matter), i.e. oligotrophic, mesotrophic, and eutrophic. The trophic states differ in the amount of accumulated sediments, concentrations of organic substances, oxygen conditions, species richness of flora and fauna and their biological structure, the degree of decomposition of organic matter, and water turbidity. Eutrophic reservoirs are characteristic of the end phase of

Table 12. Results of physicochemical parameters in selected measuring and control points in the Barycz River catchment (this study and WIOŚ data)



Point	Statistics	Physicochemical parameter											
		pH [–]	EC [μS/cm]	DO [mg/l]	BOD_5 [mg/l]	SUSP [mg/l]	NH_4-N [mg/l]	NO_3-N [mg/l]	NO_2-N [mg/l]	TKN [mg/l]	TN [mg/l]	PO_4-P [mg/l]	P [mg/l]
1A	x_{av}	7.1	622	5.4	4.6	7	0.46	3.4	0.05	1.8	5.4	0.29	0.67
	SD	0.85	120	4	6.3	8.7	0.88	3.5	0.06	0.85	3.34	0.44	0.98
1B	x_{av}	7.65	796	6.5	5.4	–	0.03	11.1	0.31	–	11.46	–	0.15
	SD	0.35	101	4.4	2.6	–	0.01	10.5	0.41	–	10.87	–	0.01
2	x_{av}	7.5	582	8.6	1.5	8	0.18	0.8	–	0.57	1.39	0.12	0.13
	SD	0.42	48	4.3	1.3	9.2	0.26	1.1	–	0.52	1.66	0.06	0.07
3	x_{av}	7.58	1044	4.8	9.3	–	6.11	2.9	–	8.46	11.3	4.04	1.81
	SD	0.2	290	2.3	7.3	–	8.41	5.7	–	9.88	7.61	5.16	2.07
4	x_{av}	7.5	1150	6.3	2.7	–	0.53	13.1	0.15	2.39	15.59	0.68	1.01
	SD	0.71	150	4.6	2.2	–	0.57	24.9	0.18	0.7	25.14	0.48	1.42
5	x_{av}	7.45	652	6.9	2.7	–	0.32	1.4	–	1.34	2.78	0.19	0.22
	SD	0.49	247	4.5	1.1	–	0.65	1.8	–	0.77	2.18	0.22	0.23
6A	x_{av}	7.25	624	8.6	2.1	–	0.18	10.4	–	1.36	11.76	0.12	0.14
	SD	0.78	95	4.2	1.8	–	0.34	10.3	–	2.34	10.25	0.14	0.13
6B	x_{av}	7.65	818	7.7	1.8	–	0.04	10	0.04	–	10.03	–	0.07
	SD	0.21	32	3.3	1.3	–	0.04	9.5	0.03	–	9.53	–	0.06
7A	x_{av}	7.05	265	6.5	3.3	–	0.63	61.3	–	1.51	2.88	0.07	0.18
	SD	0.78	23	4.7	1.7	–	0.45	2.8	–	0.65	2.84	0.62	0.06
7B	x_{av}	7.65	361	8.9	2.7	–	0.05	1.9	0.03	–	1.97	–	0.08
	SD	0.21	12	1.6	2.8	–	0.06	1.3	0.01	–	1.4	–	0.03
8A	x_{av}	7.05	265	6.5	3.3	–	0.63	1.3	–	1.51	2.88	0.07	0.18
	SD	0.78	23	4.7	1.7	–	0.45	2.8	–	0.65	2.84	0.62	0.06
8B	x_{av}	7.4	372	6.2	2.1	–	0.33	2.5	0.03	–	2.86	–	0.1
	SD	0.14	27	3.3	2.1	–	0.33	1.5	0.03	–	1.85	–	0.04

Designations in the table: 1AB – Baby reservoir; 2 – Drozdowice Wielkie; 3 – Kłoda; 4 – Orla Klatka; 5 – Pawłów Trzebnicki; 6AB – Sulmierzyce; 7AB – Szklarka Myślniewska; 8AB – Zawidze; (A – own study, B – WIOŚ); x_{av} – average value; SD – standard deviation; blue – very good ecological potential (1st class); green – good potential (2nd class); red – below the good potential (below 2nd class)

Table 13. Assessment of ecological potential at selected measuring and control points in the Barycz River catchment

Name of surface water body (name of planned reservoir)	Biological elements	Hydromorphological elements	Physicochemical elements	Ecological potential
Czarna Woda (Sulmierzyce)	II	II	BGP	III (moderate)
Kuroch (Baby)	IV	II	BGP	IV (weak)
Łacha (Drozdowice Wielkie)	III	II	BGP	III (moderate)
Orla from the spring to Rdęca (Orla Klatka)	III	II	BGP	III (moderate)
Sąsiecznica (Pawłów Trzebnicki)	II	II	BGP	III (moderate)
Śląski Rów (Kłoda)	–	II	BGP	–
Złotnica (Zawidze and Szklarka Myślniewska)	III	II	BGP	III (moderate)

Designations in the table: IV – 4th class (weak ecological potential); III – 3rd class (moderate potential); II – 2nd class (good potential); BGP – below the good potential reservoir life (reservoirs strongly overgrowing and shallowing due to the amount of accumulated organic substances, high oxygen consumption due to the richness of flora and fauna consuming oxygen, frequent eutrophication processes due to high concentrations of nutrients, thanks to which algae massively develop, high turbidity of water), oligotrophic – for the initial one (opposite characteristics to eutrophic waters), and mesotrophic – for intermediate (intermediate characteristics). (Sand-Jensen et al. 2016; Zbierska, Przybyła, & Dwornikowska 2016).

Having calculated the relevant indicators, it was estimated that all of the reservoirs exceed the dangerous phosphorus load (characteristic of the eutrophic status) (Vollenweider, 1992). Therefore, they are classified as being at risk of eutrophication (Table 14). The Orla Klatka and Kłoda reservoirs are at the highest risk (63.18 and 25.96 g · m^{-2} · year^{-1}, respectively), while the Sulmierzyce and Szklarka Myślniewska reservoirs are at the lowest risk, slightly exceeding the dangerous phosphorus load (1.58 and 1.82 g/m^{-2} · year^{-1} while the norm is approx. 1.0). This means that average phosphorus loads in the first two profiles were significantly higher than in the next two (1.81 and 1.01 g/l compared to 0.07 and 0.08 g/l), with quite a similar ratio of average reservoir depth to water retention time (62.55, 14.34, 22.53 and 22.69 m · year^{-1} respectively). In Kłoda and Orla Klatka, the phosphorus concentration mostly affected the result (1.01 and 1.81 mg/l with average median at points equal to 0.165 mg/l), while mean flow played a smaller role (0.023 and 0.373 m^3/s with median at 0.171 m^3 · s^{-1}). This is confirmed by the calculated eutrophication risk indicators for the reservoirs depending on the phosphorus load, amounting to 37.16 for the Orla Klatka reservoir, and 34.61 for the Kłoda reservoir (in other cases, the values were in the range from 1.75 to 4.99). This means that pollution of agricultural origin has the greatest influence on the risk of erosion in the analyzed points while geomorphological and hydrological conditions are less important.

The nitrogen load was determined based on the Kajak criterion (Table 8). The results indicate a risk of eutrophication from total nitrogen in all points, with the largest risk in the Orla Klatka reservoir (the permissible nitrogen load exceeded over 490 times) and the Baby reservoir (the permissible nitrogen load exceeded over 420 times), and the smallest risk in the Pawłów Trzebnicki and Drozdowice Wielkie reservoirs (19.35 and 20.34 respectively). In this case, the average annual total nitrogen concentrations and the mean annual flow rate had an equally large impact. For example, the mean total nitrogen concentration was 5.4 mg/l N in the Baby reservoir and 15.54 mg/l in the Orla Klatka reservoir. However, despite a three-fold difference in concentrations, the final result regarding the risk was similar. The obtained results show that the risk of eutrophication from nitrogen is much higher than from phosphorus in the Barycz River catchment. The risk is highest in the Orla Klatka reservoir and lowest in Pawłów Trzebnicki, Drozdowice Wielkie, and Szklarka Myślniewska.

For each point corresponding to the projected reservoir, the trophic state index (Carlson's index) was calculated (Table 15). The trophic state index was highest in the Orla Klatka and Kłoda reservoirs (103.9 and 112.3 kg P per m^2 of reservoir per year). These areas were classified as eutrophic or hypereutrophic waters, depending on the adopted classification. This means that the risk of phytoplankton blooms is highest in these reservoirs and that they are most enriched with phosphorus loads. Similarly, high results were achieved in the Baby reservoir (98.0). According to the former classification, the waters were classified as mesoeutrophic (Vollenweider, 1965), while in a new approach, these waters are hypereutrophic (Carlson & Simpson, 1996), which means that they are equally at risk of eutrophication compared to those mentioned above. The lowest values were recorded in the Drozdowice Wielkie and Sulmierzyce reservoirs (75.4 and 74.3). However, these waters are still eutrophic (according to three classifications) and mesoeutrophic (according to one of them). This means that the obtained results are consistent and the locations for water reservoirs require corrective measures.

Due to the threat to the quality of water retained in the reservoirs, the following solutions to minimize the risk are proposed further in this paper: multi-criteria assessment of the most advantageous reservoir out of the eight reservoirs planned for the construction and the use of fast/complex tools to facilitate the execution of the investment.

The analysis of the ANOVA test showed that water quality in the profiles of the reservoirs in the Barycz River catchment is determined by EC, DO, N-NH$_4$, and P. This is

Table 14. The risk of eutrophication from the phosphorus and nitrogen load in the projected water reservoirs in the Barycz River catchment

Name of reservoir (point)	DR$_T$ [m/year]	AL$_P$ [g/m^2 year]	TE$_P$ [–]	AL$_N$ [g/m^2 year]	TE$_N$ [–]
Baby (1A)	53.21	7.98	4.99	846.96	423.48
Drozdowice Wielkie (2)	29.26	3.80	3.62	40.67	20.34
Kłoda (3)	14.34	25.96	34.61	162.05	81.025
Orla Klatka (4)	62.55	63.18	37.16	975.17	487.58
Pawłów Trzebnicki (5)	13.93	3.06	4.09	38.70	19.35
Sulmierzyce (6A)	22.53	1.58	1.75	226.10	113.05
Szklarka Myślniewska (7A)	22.69	1.82	2.02	44.60	22.30
Zawidze (8A)	29.26	2.93	2.79	83.68	41.84

Designations in the table: DRT – ratio of mean depth of the reservoir to mean retention time in the reservoir; AL$_P$ – actual phosphorus load; TE$_P$ – risk of reservoir eutrophication depending on the phosphorus load; AL$_N$ – actual nitrogen load; TE$_N$ – risk of reservoir eutrophication depending on the nitrogen load.

because the differences between the mean concentrations of the physicochemical parameters were statistically significant at the assumed level of significance α = 0.05 (Table 16).

The sum of eigenvalues of the first two principal components (PCA 1 and PCA 2) was 86.9% (Table 17). As shown in Figure 3, the first principal component is correlated with EC, TN and NO_3-N. The second principal component is correlated with DO, NH_4-N, BOD_5, and P. The first principal component can be defined as a component of the influence of agricultural nutrients and conductivity; while PC2 can be defined as a component of the influence of aerobic and biogenic indicators on water quality.

Table 15. Comparison of the trophic status of projected water reservoirs in the Barycz River catchment based on the Carlson's index (1976) depending on the phosphorus load

Name of reservoir (point)	TSI_P	Trophic status of water reservoirs			
		Vollenweider [1965]	Sakamoto [1966]	EPA Survey [1974]	Carlson and Simpson [1996]
Baby (1A)	98.0	mesoeutrophy	eutrophy	eutrophy	ypereutrophy
Drozdowice Wielkie (2)	74.3	mesoeutrophy	eutrophy	eutrophy	eutrophy
Kłoda (3)	112.3	eutrophy	eutrophy	eutrophy	hypereutrophy
Orla Klatka (4)	103.9	eutrophy	eutrophy	eutrophy	hypereutrophy
Pawłów Trzebnicki (5)	81.9	mesoeutrophy	eutrophy	eutrophy	eutrophy
Sulmierzyce (6A)	75.4	mesoeutrophy	eutrophy	eutrophy	eutrophy
Szklarka Myślniewska (7A)	79.0	mesoeutrophy	eutrophy	eutrophy	eutrophy
Zawidze (8A)	79.0	mesoeutrophy	eutrophy	eutrophy	eutrophy

Table 16. Average physicochemical parameters in the water reservoirs, N = 4

Parameter	Mean Sq	F	p
EC	7.964	9.554	0.04*
DO	6.329	7.592	0.05*
BOD_5	0.009	0.011	0.92
NH_4-N	18.716	22.451	0.009*
NO_3-N	13.18	15.81	0.016
TN	1.024	1.228	0.32
P	7.11	8.529	0.04*

Mean, significance level α = 0.05;
additional determination of significance of results: $p \leq 0.05$*

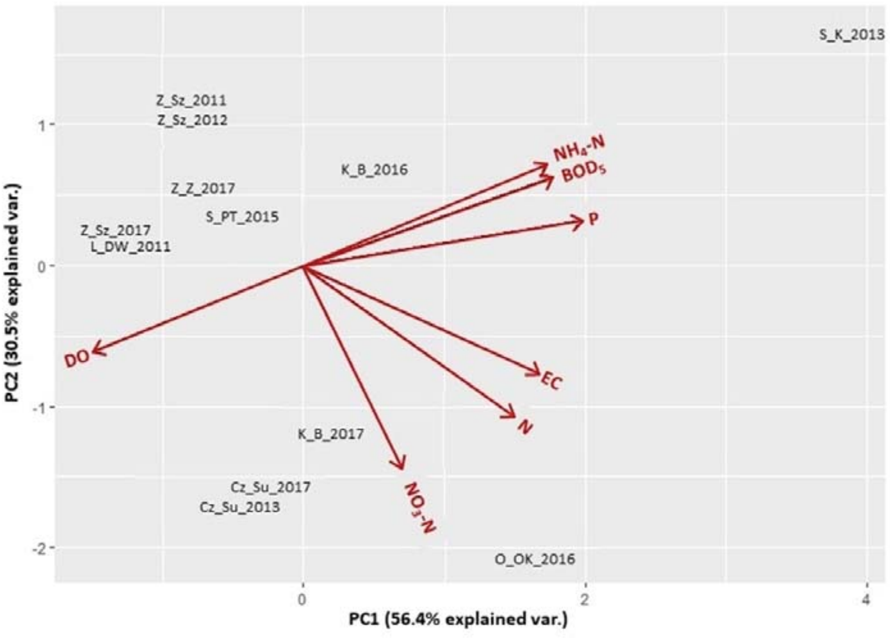


Fig. 3. PCA plots presented as samples in correlation to physicochemical parameters

Ling et al. (2017) also performed the analysis of variance at a significance level $p \leq 0.05$ and spatially assessed the changes in surface water quality in the main river and its tributaries using PCA. PCA identified a reduced number of principal components (which is explained by the 83.6% variance). The principal component (PC1) revealed that TSS, H_2S, and turbidity were the dominant pollutants in terms of water quality in the river (Ling et al. 2017). Further, BOD_5, P, and Norg were the components statistically significantly correlated with PC2.

In Özdemir's study (2016), the quality of the Kızılırmak River and its tributaries (PC1) was determined by the following physicochemical indicators: $BOD_{5,}$ COD, NH_4-N, and TKN. Similar results of water quality analysis were obtained in this paper. The quality of water was also determined by the following physicochemical indicators: BOD_5, NH_4-N, and P (Fig. 3).

Wiatkowski and Wiatkowska (2019) used PCA to assess the physicochemical parameters of the Mała Panew River, which had the greatest impact on the quality below, above, and inside the basin of the Turawa reservoir. The study showed that water quality was determined by biogenic indicators. As reported by Voza et al. (2015), in the study using PCA/FA, water quality of the Danube River (Serbia) was most strongly determined by biogenic pollutants, mineral salts and organic compounds.

Intensity of silting

The analysis of the intensity of silting (Table 18) revealed that all reservoirs have a high sedimentation rate, i.e. a high potential for accumulation of the flowing river load due to their retention properties and hydrological conditions in relation to the velocity of water flowing through the reservoirs. The calculated value varies from 87.91% in Orla Klatka to 100% in Pawłów Trzebnicki.

With a deeper insight into the factor which leads to silting, i.e. the river load (its mass, turbidity, etc.), it turns out that the conditions resulting from hydrological factors are much less important (the amount of river load is crucial). Reservoir operation times differ significantly. The smallest values were recorded in Pawłów Trzebnicki, Drozdowice Wielkie, and Szklarka Myślniewska (18, 24, and 30 years, respectively). Short operation times of these three reservoirs are caused by a strong intensity of river load transport and their projected volume (the smaller volume, the faster the rate of silting). The longest operation time is for the Sulmierzyce, Kłoda, and Baby reservoirs (340, 260, and 210 years). Long operation times result from the fact that the catchment areas of these reservoirs are located within a single mesoregion and have a similar intensity of denudation, very low in the region, which is also confirmed by low turbidity rates. Additionally, the operation time is longer for reservoirs located in places in which the river transport is lower, i.e. in lowland areas, in lower courses of rivers (Khaba & Griffiths 2017; Łabaz et al. 2014; Szatten et al. 2018; Bierman & Steig, 1996; Żmuda et al. 2009). Note that the time of proper operation of the reservoir can be significantly reduced as a result of erosion of its banks, intense at the initial stage of the reservoir exploitation. However, the amount of the material coming from abrasion is much smaller than the amount of river deposits (Kasperek et al. 2007).

Assessment of the suitability of the projected small retention reservoirs in the Barycz River catchment

Variability of the location indicator for the projected small retention reservoirs

Statistical analysis of the partial indicators used in the comparative assessment of the suitability of the reservoirs, in terms of their diagnostic properties, showed that all indicators have the coefficient of variation (V) higher than 10%. The greatest variability was found in the phosphorus load (TE_P), the nitrogen load (TE_N), and the infiltration loss coefficient (q_p). The analysis of correlation between all the indicators showed

Table 17. Summary statistics for the principal components (PCA) of physicochemical parameters in the projected water reservoirs in the Barycz River catchment

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalues	3.9487	2.1335	0.4882	0.26225	0.11439	0.050565	0.0023981
Proportion explained	0.5641	0.3048	0.06974	0.03746	0.01634	0.007224	0.0003426

Table 18. The intensity of silting for the projected reservoirs in the Barycz River catchment

Reservoir	RT_R [s]	$\bar{V}_R$ [m·s^{-1}]	SI [s^2·m^{-1}]	β [%]	Δ [g m^{-3}]	D_u [t/year]	D_1 [m^3]	t [years]
Baby (1A)	426837	0.0012557	31578730	92.05	127	1810	1514	210
Drozdowice Wielkie (2)	862198	0,0004639	172658848	97.79	2047	4192	3727	24
Kłoda (3)	1759245	0.0001776	920106068	100.00	377	271	246	260
Orla Klatka (4)	362034	0.0027331	12306338	87.91	161	1898	1517	140
Pawłów Trzebnicki (5)	2546649	0.0001047	2259460325	100.00	7926	8834	8031	18
Sulmierzyce (6A)	1118026	0.0009286	111851930	96.51	194	1540	1351	340
Szklarka Myślniewska (7A)	1223133	0.0003407	333574990	99.55	2180	6183	5595	30
Zawidze (8A)	1077667	0.0007592	131872707	97.01	505	5985	5278	120

that Pearson's correlation coefficient (r) is significantly lower than 0.7 for the assumed level of significance $\alpha = 0.05$. Therefore, all the indicators were taken into account for further analysis following the adopted criteria.

Classification of the reservoirs based on their projected locations revealed that the Ba-rycz River catchment is spatially diversified in terms of the synthetic location indicator S_l. The obtained results were interpreted as average of optimum values achieved by each reservoir (Table 19).

Out of the eight projected reservoirs in the Barycz River catchment, high synthetic location indicator S_l (Class I) was found for the Sulmierzyce reservoir (Table 19). This was due to low phosphorus load (TE_P), low nitrogen load (TE_N), considerably long silting time (t), low filtration loss indicator (q_p), and low flood-generation potential (K). The average synthetic indicators S_l (Class II) were recorded in the Baby and Kłoda reservoirs. These indicators feature low filtration losses among the reservoirs concerned, low potential safety risk, low flood-generation potential, low phosphorus load (the Baby), and nitrogen load (the Kłoda) as well as relatively favorable silting time. The most unfavorable phenomena in terms of the location possibilities occur in the catchment areas of the Szklarka Myślniewska and Zawidze reservoirs (Class IV). In spite of low phosphorus load and low nitrogen load among the reservoirs concerned, which is mainly because the catchment areas of the reservoirs are used for forest purposes, these reservoirs feature the lowest efficiency, the highest filtration losses (Szklarska Myślniewska), significantly higher flood-generation potential (Zawidze), relatively low silting time and high potential safety risk (Zawidze) among the reservoirs concerned. The indicators focus mainly on quantitative characteristics of the reservoirs which are supposed to be taken into account each time the discussion on the reservoir building is held.

Determinants of variability of location indicator for the projected small retention reservoirs

The Principal Component Analysis (PCA) revealed that the suitability of small retention reservoirs in the Barycz River catchment, in the projected locations, was differentiated due to the indicators associated with the first three principal components which corresponded to eigenvalues higher than one. The components explained about 81% of the total variability of the set of indicators (Table 20, Fig. 4).

The PCA/FA studies showed that the indicators featured high factor loads for the first principal component, which accounted for 44.650% of the total variability (Table 20). The location possibilities of the projected reservoirs in the Barycz River catchment were most strongly determined by phosphorus load (TE_P) and nitrogen load (TE_N) with high negative factor loads for the first component. The flood-generation potential (K) had a high positive factor load. Moderate positive factor loads for the first component were also observed for the silting time (t) and infiltration loss indicator (q_p). Therefore, the first principal component can be described as a component of the influence of biogenic compounds of agricultural and residential origin, and partial physiographic conditions of the catchment area, on the suitability of the reservoirs in the projected cross-sections.

The reservoir efficiency indicator (E) had a high positive factor load for the second principal component. This component explained about 20% of the total variable (Table 20). It can be described as a component of the influence of water flowing in and out of the reservoirs. The low efficiency of the reservoirs also affects the operation of the reservoirs. The location potential of the reservoirs expressed by the efficiency indicator can be improved by implementing engineering solutions (culverts, drain holes) intended for use in water reservoirs to control the outflow.

The suitability of the reservoirs in the projected cross-sections was slightly affected by the factor loads of the third

Table 19. Actual and synthetic values of partial indicators and synthetic location indicator S_l for the projected investment

Reservoir	E [–]	t [years]	K [–]	TE_P [–]	TE_N [–]	q_p [$m^3d^{-1}ha^{-1}$]	b [–]	S_l [–]	Class
Type of indicator S – stimulant D – destimulant	S	S	D	D	D	D	D	S	[–]
Baby	66.67 0.823	210.00 0.596	1.70 0.639	4.99 0.909	423.48 0.137	3.40 0.974	1.42 0.805	0.817	II
Drozdowice Wielkie	31.48 0.308	24.00 0.019	2.85 0.137	3.62 0.947	20.34 0.998	0.09 1.000	0.95 0.953	0.584	III
Kłoda	15.50 0.074	260.00 0.752	0.87 1.000	34.61 0.072	81.03 0.868	0.09 1.000	0.80 1.000	0.765	II
Orla Klatka	78.80 1.000	140.00 0.379	1.57 0.697	37.16 0.000	487.58 0.000	0.20 0.999	1.19 0.877	0.400	III
Pawłów Trzebnicki	10.46 0.000	18.00 0.000	1.30 0.811	4.09 0.934	19.35 1.000	1.29 0.990	2.35 0.513	0.533	III
Sulmierzyce	25.45 0.219	340.00 1.000	1.55 0.706	1.75 1.000	113.05 0.800	2.66 0.979	2.12 0.585	1.000	I
Szklarka Myślniewska	21.54 0.162	30.00 0.037	2.87 0.137	2.02 0.992	22.30 0.994	125.05 0.000	1.61 0.745	0.000	IV
Zawidze	24.45 0.205	120.00 0.317	3.17 0.000	2.79 0.971	41.84 0.952	4.41 0.965	3.98 0.000	0.157	IV

component (16.20%). This component can be described as a component of the influence of the potential safety risk posed by the reservoir (Table 20). Hydraulic structures intended for permanent water damming and storage are exposed to damage and breakdowns during the entire service life. The safety risk posed by the reservoirs can be minimized if natural phenomena and substratum are determined, errors made during the design and implementation phase are avoided, and hydraulic structures and facilities are properly operated (Chongxun et al. 2008; Schiozer et al. 2004).

Typology of small retention reservoirs in terms of their suitability in the projected cross-sections of the Barycz River catchment

In order to define groups of similarities for the projected small retention reservoirs in accordance with the adopted criteria, the typology was developed by means of the cluster analysis (CA). According to the obtained dendrogram, there were four statistically significant clusters of the projected reservoirs in the Barycz River catchment corresponding to 30% of the maximum binding distance (Figure 5). In each of the selected clusters with minimum cluster variability, the analyzed conditions have different influence on the suitability of the reservoirs in the projected cross-sections.

The first cluster refers to Baby and Orla Klatka (Fig. 5). These reservoirs are to be located in the areas with the lowest infiltration losses (q_p), but with relatively high pollution of agricultural origin (TE_N). The reservoirs covered by this cluster have high efficiency (E), relatively long silting time (t), and low safety risk (b). The cluster has a relatively moderate location synthetic indicator S_l (Classes II and III) (Table 19).

These reservoirs differ mainly in the amount of phosphorus compound pollution for the investment area. Orla Klatka has the highest value among the reservoirs concerned. For the optimization of this group of reservoirs, sewage discharged in their catchments should be reduced.

The second cluster describes the Sulmierzyce and Kłoda reservoirs (Fig. 5). These reservoirs are located in the areas with the relatively lowest infiltration losses (q_p), in partial catchments which are least polluted with agricultural nutrients (TE_N), and with the lowest risk of silting (t). The cluster has the relatively highest location potential synthetic indicator S_l (Classes I and II) (Table 19). The distinctive feature of this cluster is the relatively very low efficiency among the

Table 20. Factor loads, eigenvalues, variance percentage and cumulative variance percentage obtained for synthetic indicators (loads > 0.700 are marked with *)

Indicators	Factor 1	Factor 2	Factor 3
E [–]	0.644	0.713*	-0.304
t [years]	0.557	-0.515	-0.243
K [–]	0.714*	-0.528	0.243
TE_P [–]	-0.761*	0.036	-0.332
TE_N [–]	-0.827*	-0.456	0.272
q_p [$m^3 \cdot d^{-1} \cdot ha^{-1}$]	0.503	-0.451	-0.485
b [–]	0.550	0.164	0.710*
Eigenvalues	3.125	1.399	1.133
Explained part of variability [%]	44.650	19.988	16.195
Cumulative part of variability [%]	44.650	64.638	80.834

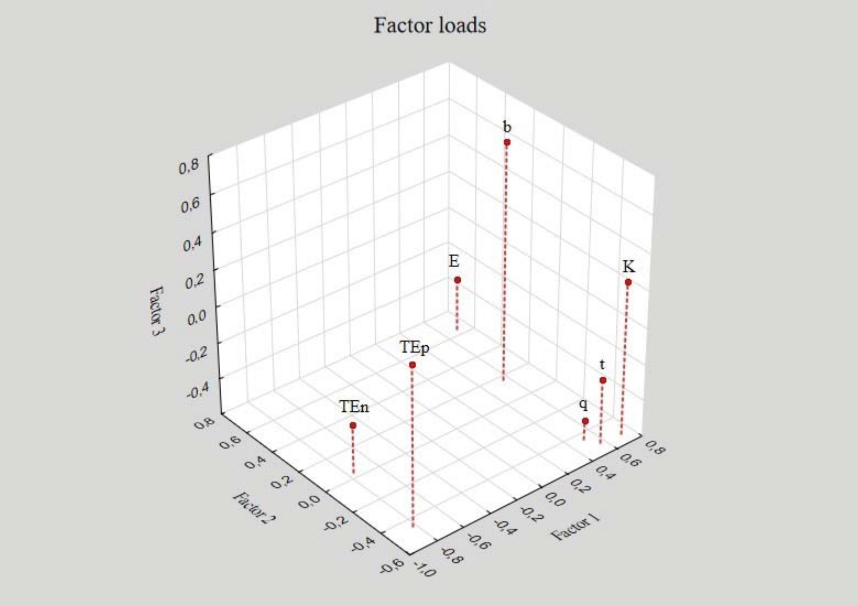


Fig. 4. Factor loads obtained for synthetic indicators

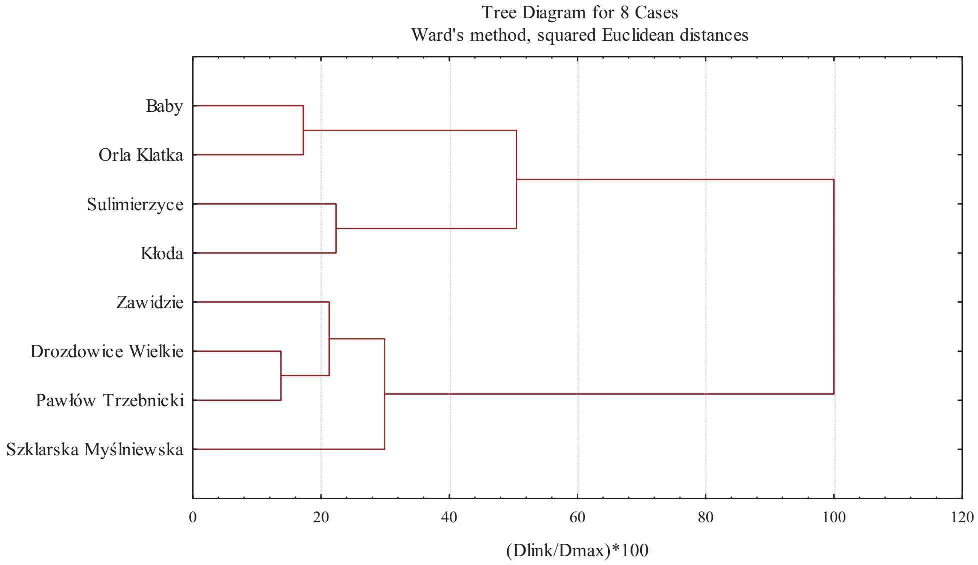


Fig. 5. Dendrogram showing hierarchical clustering of water reservoir agglomeration with the Ward's method

reservoirs concerned. Optimization in the group of these reservoirs should concern the improvement of their efficiency.

The third cluster contains three reservoirs: Drozdowice Wielkie, Pawłów, and Zawidze. These reservoirs are located in the areas with the relatively lowest pollution from nitrogen load (TE_N) and phosphorus load (TE_P), and the most favorable infiltration processes among the reservoirs concerned. The cluster has the relatively lowest reservoir efficiency indicator (E) and one of the highest risks of silting. The reservoirs differ mainly in the safety risk (b) and flood-generation potential (K). The safety risk in Zawidze is high and its flood-generation potential is highest in the analyzed group. For the optimization of the reservoirs forming this cluster, hydrological conditions should be improved in relation to the equalization of water flows in the watercourses and extending the silting time as well as verification of the parameters of the planned reservoirs in relation to the damming height and reservoir volume.

The last, fourth, one-element cluster describes Szklarka Myślniewska. This was recognized as a separate cluster because the reservoir has poor efficiency (E) and relatively short silting time (t). Moreover, it is likely to lead to high water levels and floods, and has the highest filtration losses in terms of the geological substratum. This catchment has the relatively lowest pollution from nitrogen load (TE_N) and phosphorus load (TE_P). The cluster has the relatively lowest location synthetic indicator S_l (Class IV) (Table 19). For optimization of this reservoir, hydrological conditions should be improved in relation to the equalization of water flows in the watercourses and extension of the silting time as well as the need to seal the substrate and additional financial outlays due to the highest risk of filtration losses among the reservoirs concerned.

Summary and conclusions

Currently, due to reduced water resources, there is a need to build water reservoirs. The decision to build them brings a number of challenges. Despite many advantages water reservoirs offer, the factors which may affect the functionality of the reservoir, as required, should be identified before the project is implemented. In particular, it is necessary to perform complex analyses and determine a number of factors, including hydrological conditions, water quality, the intensity of silting, hydrogeological conditions, and safety considerations, decisive for the suitability of the project. The relations between particular catchment properties and parameters for water quality and quantity are extremely essential for monitoring changes in the catchments and forecasting hydrological phenomena, especially in uncontrolled catchments. Therefore, it is necessary to properly identify the structures and interrelationships between the factors determining the suitability of reservoirs, and identify obstacles and limitations. It is also required to minimize the identified risks in the reservoir catchment (improvement of water and sewage management, appropriate agricultural management), basin, and dam.

The conclusions drawn from the studies and analyses regarding cross-sections of the eight projected small retention reservoirs in the Barycz River catchment are the following:

1. The highest minimum acceptable flows (Q_i) and natural design flows (Q_{au}) were identified in the Baby profile while the highest available flow (Q_d) and maximum flow (Q_{max}) were determined in the Zawidze profile (Tab. 10). The available flow is dependent on average annual available flows SSQ, which, like Q_{max}, was highest in the Zawidze profile. The minimum acceptable and natural design flow depends on the adopted parameters. The lowest values of flows were obtained for the Kłoda profile.
2. In terms of water supply, Pawłów Trzebnicki proved to be the best reservoir (B = 8.1%, Tab. 11). In terms of flood reduction, the best reservoir compensation indicator at α = 90% was achieved by Baby, Orla Klatka, and Sulmierzyce. As a multi-purpose reservoir, Orla Klatka obtained the best hydrological parameters in terms of flood reduction and water supply, with the efficiency at E = 78.8%.
3. The PCA revealed the influence of the indicators on the water quality in the reservoirs. The most strongly determined indicators, i.e. electrolytic conductivity, total nitrogen, and nitrate nitrogen, were included in the first

principal component. This component can be described as a component of the influence of agricultural nutrients and conductivity. The second principal component covered dissolved oxygen, ammonium nitrogen, BOD_5, and total phosphorus. This component was described as a component of the influence of oxygen and biogenic indicators on water quality.

4. The norms of physicochemical parameters were exceeded at all measuring and control points, especially for nutrients (Tab. 12). Orla Klatka and Kłoda are most susceptible to eutrophication.
5. In all the profiles except Baby, the ecological potential was moderate or weak. SWB is strongly altered, which is due to physicochemical factors. Similarly, all the analyzed waters in the profiles were classified as eutrophic. In the case of the decision to build the reservoir, corrective measures should be applied in the catchment and the basin.
6. The expected service life of each of the eight reservoirs varies, ranging from 18 for Pawłów Trzebnicki to 340 years for Sulmierzyce. The smaller the volume and area of the reservoir and the higher the reservoir is located in the river course (where river load deposit processes are most intensive), the shorter the service life.
7. In order to comprehensively assess the possibilities of the reservoir locations, the synthetic indicator S_l was adopted. The highest S_l was found in Sulmierzyce. This reservoir is located in the areas with the lowest catchment pollution from partial agricultural nutrients (TE_N), the relatively lowest infiltration losses (q_p) and the lowest risk of silting (t). The lowest location synthetic indicator S_l was identified in Szklarka Myślniewska. This reservoir has poor efficiency (E) and relatively short silting time (t). Moreover, it is likely to lead to high water levels and floods and has the highest filtration losses in terms of the geological substratum. This catchment has the relatively lowest pollution from nitrogen load (TE_N) and phosphorus load (TE_P), but requires optimization measures in the field of hydrology and hydroengineering at the design stage.
8. On the basis of PCA/FA studies, a model of structures and relationships between factors was developed to determine the suitability of small retention reservoirs in the Barycz River catchment. The location potential was most strongly determined by the following indicators: phosphorus load (TE_P), nitrogen load (TE_N) and flood-generation potential (K), included in the first principal component. This component can be described as a component of the influence of biogenic compounds and flood-generation potential on the suitability of the reservoirs in the projected cross-sections. The second principal component concerned the reservoir efficiency indicator (E). This component was described as a component of the influence of water retention capacity on the potential of optimum locations. The safety risk posed by the reservoirs (b) corresponded to the third principal component. This component was described as a component of the influence of potential risk posed by the reservoir.
9. The cluster analysis (CA) was used to clearly identify clusters of reservoirs, each with minimum differentiation of partial indicators. Sulmierzyce and Kłoda were assigned to the cluster with the highest location synthetic indicator S_l among the reservoirs concerned (Classes I and II). This cluster has relatively very low efficiency among the reservoirs concerned, and requires hydrological optimization measures. Szklarka Myślniewska formed a separate one-element cluster with the relatively lowest location synthetic indicator S_l (Class IV), despite the fact that its catchment has the relatively lowest pollution from nitrogen load (TE_N) and phosphorus load (TE_P). This reservoir will encounter many obstacles and limitations, mainly due to poor efficiency (E), and relatively short silting time (t). Moreover, the reservoir is likely to lead to high water levels and floods and has the highest filtration losses in terms of the geological substratum. The reservoir covered by this cluster requires a number of hydrological and hydroengineering optimization measures.
10. The solutions proposed in this paper are intended to support the analysis of a variety of problems encountered in the implementation of small retention reservoirs in terms of the need to increase water resources. They provide new and comprehensive information necessary for identifying possibilities and obstacles of building small retention reservoirs, with particular focus on conditions and resources.

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Ocena możliwości realizacji zbiorników małej retencji w kontekście potrzeby zwiększania zasobów wodnych

Streszczenie: Obecnie w Polsce z powodu zmniejszonych zasobów wodnych istnieje potrzeba budowy zbiorników wodnych. Pełnią one w środowisku ważne funkcje gospodarcze, przyrodnicze, rekreacyjne, poprawiają bilans wodny i przyczyniają się do ochrony przeciwpowodziowej. Budując zbiornik wodny, oprócz zagadnień hydrologicznych związanych z ilością wody, należy wziąć pod uwagę jakość wody, która będzie retencjonowana w zbiorniku, jego zamulenie oraz szereg innych aspektów. Bardzo ważna jest więc analiza uwarunkowań zbiorników planowanych, w tym fizjograficznych, hydrologicznych, hydrochemicznych i hydrogeologicznych, aby ograniczyć potencjalne negatywne skutki podejmowania decyzji o budowie takich obiektów. W celu oceny możliwości realizacji ośmiu planowanych zbiorników małej retencji wodnej w kontekście potrzeby zwiększania zasobów wodnych na obszarze zlewni Barycz w województwie dolnośląskim i wielkopolskim w niniejszym artykule uwzględniono wskaźniki hydrologiczne (sprawność zbiornika, czas eksploatacji ze względu na intensywność zamulania, wskaźnik potencjalnego zagrożenia powodzią), jakości wody (obciążenie ładunkiem fosforu i azotu), hydrogeologiczne (rodzaj podłoża geologicznego pod czaszę zbiornika wodnego i straty filtracyjne) oraz bezpieczeństwa zapory zbiornika. Do opracowania teoretycznego modelu, opisującego prawidłowości zachodzące pomiędzy tymi wskaźnikami, wykorzystano wielowymiarowe techniki statystyczne takie jak: Principal Component Analysis (PCA) i Factor Analysis (FA). W celu oceny planowanych zbiorników w aspekcie najbardziej korzystnych do realizacji opracowano syntetyczny wskaźnik, który umożliwił porównanie tych zbiorników w odniesieniu do rozpatrywanych uwarunkowań. Wykonano również z zastosowaniem Cluster Analysis (CA) typologiczną klasyfikację planowanych zbiorników małej retencji wodnej pod względem jednorodnych lokalizacji na analizowanym obszarze. Zaproponowana w niniejszej pracy autorska procedura badawcza identyfikacji najkorzystniejszych, spośród planowanych do realizacji, zbiorników wodnych z zastosowaniem wielowymiarowych technik statystycznych, może posłużyć jako narzędzie wspomagające podejmowanie decyzji przy innych obiektach planowanych do realizacji w wojewódzkich planach rozwoju małej retencji.